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Hydraulic resistance identification and optimal pressure control of district heating network

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A B S T R A C T

Hydraulic performance of district heating (DH) network is the key to energy reduction of DH system. Efficient hydraulic operation strategy requires precise values of the hydraulic resistances of pipelines. In this paper, a hydraulic resistance identification method was developed. With this method, precise hydraulic resistances of all the pipelines in the DH network can be obtained based on the pressure and flow rate values observed at the heating substations under different hydraulic conditions. An optimal pressure control strategy of DH network was established based on the identified hydraulic resistances for energy reduction of the pumping systems. The feasibility and effectiveness of the hydraulic resistance identification method were analyzed with the well-developed hydraulic simulation technique of district heating network realized in Matlab environment. Hydraulic performances of the optimal pressure control (OPC) strategy were compared with the traditional constant pressure difference control (CPDC) strategy. Results show that the pumping energy of DH system under the control of CPDC can be reduced by 14.6% compared with OPC during the heating period.

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1. Introduction

The district heating (DH) system is an indispensable infrustructure for heating in northern China. Recently, new concepts and techniques on the 4th generation DH (4GDH) network have been proposed and widely discussed [1,2]. In the 4GDH network, renewables such as solar thermal energy [3] and industrial waste heat [4,5] can be integrated to the district heating network to improve the energy efficiency and environmental effects of DH system, but this requires the hydraulic condition of the primary DH network to be more flexible and efficient. The optimal control strategy of the primary DH network is an important ensurance for efficient operation and control of the 4GDH network. And the simulation and optimization of concrete technical solutions provide the necessary insights and information to support the transformation process towards sustainable energy systems [6].

The predictive control strategy is an efficient operation technique to optimize the supply temperature of the DH systems dynamically. The predictive control strategy calculates the time series of the future supply temperature set-points and minimizes the total energy consumption of DH network. Controller tuning method for the nonlinear predictive control of the DH network was developed by Dobos and Abonyi [7]. Steer et al.'s study [8] showed that in predictive control of the DH networks, the adjustment frequency of the supply temperature set-point influences the overall operating cost in two ways: adaptability to changes in network conditions and availability of time for determining an appropriate response. The predictive control strategy mainly deals with dynamic supply temperature optimization of the DH network.

Steady state methods for modeling and operational optimization of the DH networks have also been widely studied. Li et al. [9] developed an integrated multi-scale modeling method to simulate the operation performance of CHP based district heating system, including the heat loss, pressure drop, pump power and supply temperatures. Wang et al. [10] established a mathematical model describing the steady-state thermal conditions of the DH systems with a model parameter calibration method. Intelligent optimization algorithms such as the Genetic Algorithm (GA) and the Group Search Optimizer (GSO) are effective in solving operational optimization problems of DH network. Jie et al. [11] solved the optimization problem of reducing pumping and heat loss cost to determine the heating parameters with MATLAB. Jiang et al. [12] developed a GSO based optimal operation strategy of an integrated energy based DH system to minimize the fossil fuel consumption by optimizing the boiler set-point temperature and

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Nomenclature

a_{ij}	element of the basic incidence matrix A
A	basic incidence matrix of the supply pipeline network
a_p, b_p, c_p	parameters of pump head characteristic equation
B	intermittent matrix for hydraulic resistance identification
CPDC	constant pressure difference control
d	vector diagonalization notation
D	inner diameter of the pipeline (m)
DH	district heating
E_u	constant matrix that extracts the pressures of heating substation nodes from the node pressure vector
f	Darcy friction factor
F	operating frequency of pump
F_o	power frequency
g	volume flow rate of the pipeline (m^3/h)
G	column vector of the pipeline flow rates (m^3/h)
H_p	pump head (m)
$H_{p,min}$	the minimum pump head (m)
I	column vector, of which the elements are all ones
K_i	loss coefficients of the local losses
$K_{v,i}$	valve flow capacity
l	length of the pipeline (m)
L	number of operating conditions for identification
M	number of heating substation
N	number of pipelines in the DH network
OPC	optimal pressure control
P	column vector of the node pressures (Pa)
P_u	column vector of the heating users' pressures at the supply side (Pa)
Q	column vector of net flow rates of all the nodes in the network (m^3/h)
q	net flow rate of node (m^3/h)
$q_{u,i}$	required flow rate of heating substation (m^3/h)
q_p	the pump flow rate (m^3/h)
r	frequency ratio
R_i	the rangeability of the valve
s	hydraulic resistance of pipeline (Pa h^2/m^6)
s_u	total internal hydraulic resistance pipe, heat exchanger and pipeline accessories except for the control valve in the heating substation (Pa h^2/m^6)
S	column vector of the pipeline hydraulic resistances (Pa h^2/m^6)
S_{id}	identified hydraulic resistance vector of S (Pa h^2/m^6)
W_p	pump power (W)
x_i	valve opening
Y	nonlinear function for hydraulic simulation
Δp	pressure drop of pipeline (Pa)
$\Delta P_{u,a}$	column vector of available supply and return pressure differences of all the heating substations (Pa)
$\Delta P_{u,n}$	column vector of the needed supply and return pressure differences of all the heating substations (Pa)
ΔP_v	column vector of valve pressure drops in heating substations (Pa)
α_p, β_p, γ_p	parameters of pump efficiency characteristic equation
ρ	density of hot water (kg/m^3)
η	pump efficiency

pump water flow rate. Fang and Lahdelma [13] established a GA based operation optimization strategy to minimize the combined production and distribution costs of the DH network. These works are very remarkable in operational optimization of the flow rate and supply temperature of the DH network. But there is still a large potential in further improvement of the DH network hydraulic performance by minimizing the pump head to provide the needed pressure difference and flow rate demand for each heating substation.

For large scale DH networks, the hydraulic performances are usually not at the optimum conditions [14], which may lead to high pumping cost. Hydraulic performance simulation and optimization of DH networks have also been studied. An efficient method for numerical simulation and analysis of the steady state hydraulics of complex pipeline networks based on network loop model and the square root method was developed by Stevanovic et al. [15]. In order to optimize the total pump power of large district heating network with multiple heat sources, a reduced model based on the Proper Orthogonal Decomposition combined with Radial basis functions was proposed by Elisa et al. [16], which allowed maintaining high level of accuracy despite reductions of more than 80% of the computational time compared with the CFD method. Vesterlund et al. [17] developed a method for modeling and simulating complex DH networks to optimize the total operating costs of a multi-source network, with constraints on the pressure and temperature levels in the user areas and on the heat generation characteristics at each production site. In our previous work, the GRG optimization algorithm based hydraulic optimization control strategy was developed for the meshed DH network with multiple heat sources [18], which minimizes the total pumping power by optimizing the pump frequencies at the heat sources and valve openings at the heating substations.

The preceding optimization approaches concerning hydraulic condition optimization require the hydraulic resistance parameters of the pipelines in the DH network. In the previous approaches, the hydraulic resistances of DH network are basically obtained by Darcy–Weisbach formula according to the dimension and the estimated Darcy friction factor of the pipes. The hydraulic resistances determined by Darcy–Weisbach formula are the theoretical values of the pipes, which are usually applied to network design, pump selection and network hydraulic performance evaluation. However, the real values of hydraulic resistances may be very different from the values determined by Darcy–Weisbach formula, due to the pipe corrosion, fouling and missing information of pipe fittings, which will always exist in real network and cause the theoretical values of pipe hydraulic resistances obtained with the Darcy–Weisbach formula different from the real values. Hence, the estimated Darcy friction factor may not match the real case, which may decrease the efficiency of the optimization operation. Transition of the previous DH network towards the 4GDH network also calls for effective techniques for deriving the network hydraulic resistances with good accuracy to ensure the operational optimization strategy working efficiently.

In this paper, an identification method for obtaining the hydraulic resistances of the DH pipelines was developed. The method utilizes the observed values of pressures and flow rates under different operation conditions of the DH network to evaluate the hydraulic resistances of the pipelines of DH networks. The feasibility and effectiveness of the hydraulic resistance identification

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